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Some Aspects of Indian Monsoon Depressions and the Associated Rainfall

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ABSTRACT—This study is based on all the monsoon depressions that moved westward across India between Calcutta, Allahabad, and Delhi on the right and Gopalpur, Nagpur, and Ahmadabad on the left during July and August for the period 1891–1960. Statistical distributions of 24-hr motion and of the intensity of the depression, the relation between 24-hr motion and concurrent 24-hr rainfall, and the relation between the intensity of the depression and subsequent 24-hr rainfall are examined. In addition, the average rainfall per depression day and its standard deviation, the contribution of depression rainfall to the total rainfall, and the efficiency of the depression as a rain giver are computed. Mean patterns of 24-hr rainfall within 500 km of the center of the depression along longitudes 87°E, 80°E, and 75°E are obtained, and the main points of difference between them are discussed.

In the quadrants to the right of the depression track, the rainfall field is flat. In the quadrants to the left, however, large gradients of rainfall exist, particularly along and west of 80°E; the maximum rainfall is located in the left front quadrant, about 150 km from the center and 50–150 km from the depression track. Heavy rainfall extends about 250 km from the depression track in the left sector. Reasons for maximum rainfall in the left front quadrant were sought. We examined statistical distributions of 24-hr rainfall in the four quadrants of depression along the three longitudes and found that the gamma probability model gives a good fit to 24-hr rainfall in each of the four quadrants of depression. Using the gamma model, we computed probabilities of rainfall of different intensities in the four quadrants. In this study, orography within the sector is kept constant by considering the rainfall from the same set of rain gage stations along each of the three longitudes.

1. INTRODUCTION

During the summer monsoon season (June to September inclusive), depressions form in the north Bay of Bengal and move in a westerly direction across India. These cyclonic systems range in intensity from low-pressure areas to cyclonic storms. In addition to providing beneficial rainfall along and near their tracks, these systems transport heat and moisture upward and maintain the activity of the monsoon trough. Ramanathan and Ramakrishnan (1933), Sur (1933), Desai (1951) and Desai and Koteswaram (1951) studied monsoon depressions during July and August and the associated 24-hr rainfall. Pisharoty and Asnani (1957) prepared composite charts of rainfall around four monsoon depressions during July and August; they found that, on any particular morning, the heavy rainfall ($\geq$75 mm in 24 hr) area extends to about 500 km ahead of and behind the depression center on that morning and that this area (about 400 km in width) lies to the south of the track. Lal and Rai Sircar (1960) studied 5-day rainfall associated with a monsoon storm/depression in August 1957. Raghavan (1967) studied the influence of monsoon storms/depressions in July and August during 1948–57 on the monthly rainfall for July and August in India. Dhar and Mhaiskar (1970) studied the rainfall distribution around the tracks of tropical disturbances (storms/depressions) over coastal Orissa; their study is based on 10 storms/depressions during the June–October period from 1931–50. They found that the heavy rainfall occurred roughly between distances 40 and 120 km on the left side of the track on the day the system crossed the coast and on the day before. Koteswaram and George (1958) studied the causative factors of depression formation in the Bay of Bengal, and Rao and Jayaraman (1958) made a statistical study of the depressions/storms in the Bay of Bengal.

In the present study, we consider some of the important features of the Indian monsoon depressions and the associated 24-hr rainfall during July and August in the 70-yr period 1891–1960 along three longitudes. The study is confined to the depressions during July and August only, since these depressions have uniform characteristics and generally move in a direction between west and north-northwest without recurving.

Composite pictures of depression rainfall generally involve highly variable orography and variations due to longitude. Rainfall is highly dependent on orography, however, and the characteristics of depressions are not uniform over the longitudinal extent of India. In this study, therefore, we investigate features of depression rainfall along three mean longitudes. By following a new approach, we keep the stations for which mean rainfall is considered in the same sector of the depression along each longitude, and we hold orography constant within each sector by considering the rainfall at the same set of stations in each case of monsoon depression.

2. DEPRESSIONS SELECTED FOR STUDY

Depression tracks (India Meteorological Department 1964) were examined. An overwhelming majority of the depressions form in the Bay of Bengal north of 20°N

TABLE 1.—*The number of Indian monsoon depressions that crossed the different longitudes and the latitudinal belt in which the depressions crossed during the period 1891–1960*

Month	90°E	85°E	80°E	75°E	70°E
July	12 (19°–23°N)	96 (20°–25°N)	59 (21°–26°N)	25 (23°–27°N)	12 (23°–27°N)
August	15 (19°–23°N)	103 (18°–24°N)	67 (20°–26°N)	27 (22°–27°N)	2 (22°–27°N)
Total	27 (19°–23°N)	199 (18°–25°N)	126 (20°–26°N)	52 (22°–27°N)	14 (22°–27°N)

TABLE 2.—*The number of depression tracks lying within the belt formed by the lines Calcutta–Allahabad–Delhi and Gopalpur–Nagpur–Ahmadabad during the period 1891–1960*

July		August		July & Aug.		Percentage within the belt
Within	Outside	Within	Outside	Within	Outside	July & Aug.
115	10	119	13	234	23	91

and move in a westerly direction. Only a few survive as depressions by the time they reach longitude 70°E. Table 1 gives the number of depressions and the latitudinal belt in which the depressions crossed longitudes 90°, 85°, 80°, 75°, and 70°E during the period 1891–1960. The latitudinal belt is given in parentheses.

Table 1 shows that about 60 percent of the westerly moving depressions that cross the Bengal-Orissa coast (85°E) survive west of 80°E; 25 percent, west of 75°E; and only 7 percent, west of 70°E. The number of depressions crossing longitude 90°E is small.

We selected for study all depressions during the period 1891–1960 that had tracks lying within the belt formed by the lines Calcutta–Allahabad–Delhi (CAL–ALB–DLH) and Gopalpur–Nagpur–Ahmadabad (GPL–NGP–AHM) as shown in figure 1. Recurving depressions and storm stages were not considered. During this 70-yr period, about 90 percent of the depression tracks lay within this belt (table 2). Note that the selected depressions always have Calcutta, Allahabad, and Delhi in their right sectors and Gopalpur, Nagpur, and Ahmadabad in their left sectors, with reference to the directions of movement.

3. DATA

The following depression data were collected:

1. The bearings of the six stations, Calcutta, Allahabad, Delhi, Gopalpur, Nagpur, and Ahmadabad with respect to the 24-hr mean depression center and the direction of the motion during the 24-hr period from about 0300 GMT of one day to about 0300 GMT of the next. Depression centers (India Meteorological Department 1964) were used. If we let D_1 and D_2 be the positions of the depression centers at the beginning and end of the 24-hr period, respectively, and then assume uniform motion during the 24-hr period, then D_m, the midpoint between D_1 and D_2, is the 24-hr mean position of the depression center. The quantities measured are D_mN (the distance between D_m and the rain gage station, N) and the angle θ as shown in figure 2. Only those cases where $D_mN \leq 500$ km and

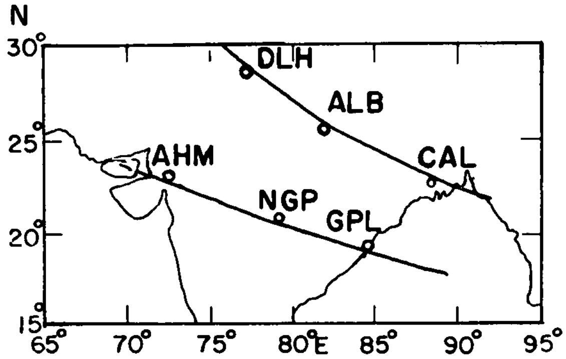

FIGURE 1.—Map showing the belt from which depressions were considered.

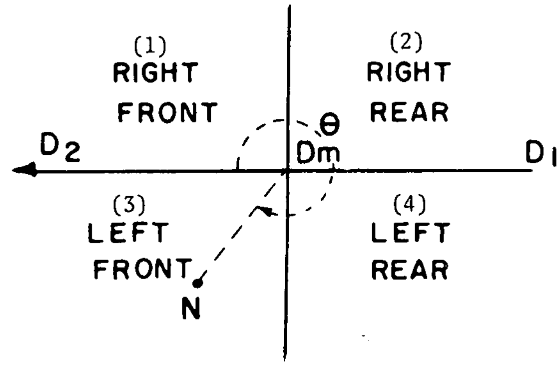

FIGURE 2.—Quadrants of a depression.

either $D_1N \leq 500$ km or $D_2N \leq 500$ km were considered. The first condition was imposed because heavy rainfall is generally found to be within this distance, and the second one was imposed to ensure that the station was within 500 km of the depression center for more than 12 hr. It is possible to visualize a situation wherein both D_1N and D_2N exceeded 500 km, but D_mN was within this distance for only a short time. Such situations, though small in number, had to be excluded by imposing the second condition since the influence of the depression on the station rainfall is small in these situations.

2. D_1D_2, the 24-hr movement of the depression center.

3. The intensity of the depression. As a measure of intensity, we adopted the pressure difference given by the normal mean sea-level pressure minus the actual mean sea-level pressure over the central region of the depression. Five-day normals of mean sea-level pressure (based on data for 1931–60) published by the India Meteorological Department (1965) were used. Since only the 0300 GMT sea-level pressure charts are available for the period 1891–1960, the intensity of the depression could be obtained for 0300 GMT only; that is, at the beginning of the 24-hr period for which rainfall has been considered.

4. The quadrant of the depression in which the station lay (fig. 2).

5. Rainfall data. Twenty-four hour rainfall data (from 0300 GMT of one day to 0300 GMT of the next) was collected for Calcutta (Alipore), Allahabad, Delhi, Gopalpur, Nagpur, and Ahmadabad in all the cases considered. In addition, rainfall values for three selected stations around each of these six stations were collected. The selected stations, shown in figure 3, were chosen in such

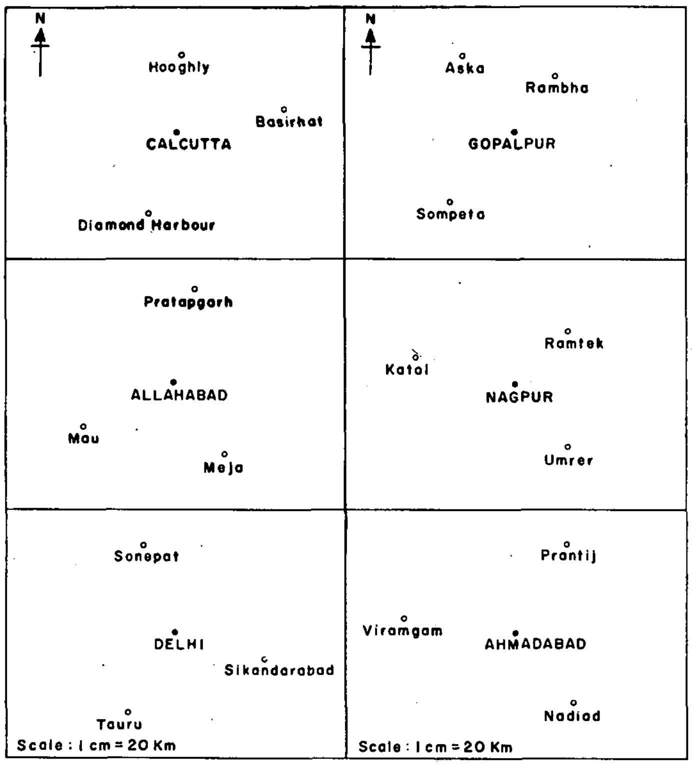

FIGURE 3.—Stations selected around Calcutta, Gopalpur, Allahabad, Nagpur, Delhi, and Ahmadabad, India.

a way that each is about 50 km from its central station, and the three stations are approximately located at the vertices of an equilateral triangle. Rainfall for the central and surrounding stations was obtained from the available punched cards and the volumes of "Daily Rainfall of India" (1891–1960) compiled by the India Meteorological Department, Poona. The average of the rainfall at the four stations (one central and three surrounding stations) is expected to provide a suitable, stable, and representative figure for the 24-hr rainfall within a 50-km radius of the central station. This average rainfall was obtained for the areas around each one of the central stations for all the occasions and has been used in this study as rainfall associated with depressions.

4. THE 24-HOUR MOVEMENT OF DEPRESSIONS AND ITS POSSIBLE RELATION TO CONCURRENT 24-HOUR RAINFALL

In the case of intense cyclonic systems, rainfall is most closely associated with the slower moving systems. We wish to determine if a similar relationship exists in the case of weaker systems such as depressions.

First, however, we must study the distribution of 24-hr depression movement. Table 3 gives the frequency distribution of 24-hr depression movement for each area surrounding the six central stations. The distribution is right-skewed with mode between 225 and 300 km. The mean and the median are about 300 km and 270 km, respectively, along 87°E, and there is a relatively small increase westward. The standard deviation is about 50 percent of the mean. Frequency falls off rapidly beyond 600 km. About 2/3 of the distribution is contained between 150 and 450 km.

TABLE 3.—*Frequency distribution of 24-hr movement of depressions during July and August combined, for the period 1891–1960*

24-hr movement (D_1D_2) (km)	Frequency for the area*					
	Calcutta	Gopalpur	Allahabad	Nagpur	Delhi	Ahmadabad
$D_1D_2 \leq 75$	11	12	4	2	0	0
$75 < D_1D_2 \leq 150$	52	56	39	29	17	6
$150 < D_1D_2 \leq 225$	43	53	48	47	12	5
$225 < D_1D_2 \leq 300$	60	74	72	66	30	19
$300 < D_1D_2 \leq 375$	40	49	50	52	13	15
$375 < D_1D_2 \leq 450$	30	34	38	31	11	12
$450 < D_1D_2 \leq 525$	19	24	25	23	7	8
$525 < D_1D_2 \leq 600$	18	26	21	27	4	4
$600 < D_1D_2 \leq 675$	5	6	12	12	4	7
$675 < D_1D_2 \leq 750$	1	1	1	3	0	1
$750 < D_1D_2$	0	1	3	5	0	1
Total	279	336	313	297	98	78
Median of distribution (km)	270	270	300	320	290	345
Mean of distribution (km)	289	297	324	340	303	372
S.D. of distribution (km)	147	149	154	159	141	155

*Area within 50-km radius of station.

The moment coefficients of skewness and kurtosis, g_1 and g_2, respectively, were computed for the distribution of the 24-hr depression movement, and the significance of their departures from zero was tested. In addition, the normal distribution was fitted to the distribution, and the chi-square test of goodness-of-fit was applied. The significance of the g_1, g_2, and chi-square values indicates that the distribution of 24-hr movement of the depression is highly non-normal. By fitting the gamma distribution, which covers a wide range of skewness, and applying the chi-square test of goodness-of-fit, we found that the gamma probability distribution gives a good fit to the 24-hr movement of the depresssion. The scale parameter of the fitted gamma distribution decreases westward, from 81 to 68 km, whereas the shape parameter increases westward, from 3.5 to 5.5

Table 4 gives the correlation coefficients between the 24-hr movement of the depression and rainfall during the same 24-hr period, obtained after normalizing the two variates by the simple square root and cube root transformations—normality of distribution is assumed in testing the significance of the correlation coefficient. The significance of the correlation coefficient has been tested by using the standard error of the correlation coefficient and adopting the 5-percent level of significance, as suggested by Brooks and Carruthers (1953). They show that, for $n > 25$, the value significant at the 5-percent level obtained from the standard error of the correlation coefficient, given by $1/\sqrt{n-1}$, is accurate when the null hypothesis of no correlation is to be tested. McDonald (1960) has justified the use of σ_r, the standard error of the correlation coefficient, for applying geophysically adequate significance tests and for obtaining the confidence limits for r. Only at Gopalpur and Nagpur are the correlation coefficients relating rainfall and depression movement significant at the 1-percent level. Slower moving depressions give higher rainfall at Gopal-

TABLE 4.—*Correlation coefficient between 24-hr depression rainfall and movement of depression during the same 24-hr period*

Area*	No. of observations	Correlation coefficient from data normalized by	
		Square root transformation	Cube root transformation
Calcutta	279	0. 041	0. 050
Gopalpur	336	−. 162‡	−. 144‡
Allahabad	313	−. 035	−. 050
Nagpur	297	. 166‡	. 172‡
Delhi	98	−. 113	−. 092
Ahmadabad	78	. 169	. 167

*Area within 50-km radius of station
‡Significant at the 1-percent level

TABLE 5.—*Frequency distribution of depression intensity during July and August combined, for the period 1891–1960*

Intensity Δp (mb)	Frequency for the area*					
	Calcutta	Gopalpur	Allahabad	Nagpur	Delhi	Ahmadabad
$\Delta p<2$	2	3	8	8	6	2
$2\leq\Delta p<4$	43	49	45	40	22	8
$4\leq\Delta p<6$	73	81	78	73	27	18
$6\leq\Delta p<8$	72	87	73	76	23	19
$8\leq\Delta p<10$	59	73	64	59	13	18
$10\leq\Delta p<12$	21	32	39	35	5	11
$12\leq\Delta p<14$	9	11	6	6	1	1
$14\leq\Delta p$	0	0	0	0	1	1
Total	279	336	313	297	98	78
Median of distribution (mb)	6	6	6	6	5	7
Mean of distribution (mb)	6. 3	6. 4	6. 3	6. 3	5. 2	6. 7
S.D. of distribution	2. 6	2. 7	2. 7	2. 7	2. 9	2. 7

*Area within 50-km radius of station

pur. At Nagpur, however, faster moving depressions appear to give higher rainfall; here, faster moving depressions may have higher intensity.

5. INTENSITY OF DEPRESSIONS AND RELATION TO SUBSEQUENT 24-HOUR RAINFALL

The frequency distribution of the intensity of depressions is given in table 5. The distribution appears to be right-skewed. Fifty percent of the distribution is contained in the 4- to 8-mb range, and about 85 percent of the distribution is contained in the 2- to 10-mb range. The mean and the median of the distribution are 6.3 mb and 6.0 mb, respectively. The standard deviation is 2.7 mb.

Tests for the hypotheses of normal and gamma distributions were applied to the distribution of the intensity of depressions and neither of these distributions gives a good fit to the intensity distribution.

The correlation coefficient between the intensity of depressions at 0300 GMT and the subsequent 24-hr rainfall obtained after the normalization of the variates has been given in table 6. Except for those depressions affecting Gopalpur, the correlation coefficient between the intensity of the depression and the subsequent 24-hr rainfall is

TABLE 6.—*Correlation coefficient between intensity of depression at 0300 GMT and rainfall during the subsequent 24 hr*

Area*	Number of observations	Correlation coefficient from data normalized by	
		Square root transformation	Cube root transformation
Calcutta	279	0. 117†	0. 138†
Gopalpur	336	−. 051	−. 062
Allahabad	313	−. 172‡	−. 166‡
Nagpur	297	. 380‡	. 400‡
Delhi	98	−. 211†	−. 213†
Ahmadabad	78	. 221†	. 260†

*Area within 50-km radius of station
†Significant at the 5-percent level
‡Significant at the 1-percent level

TABLE 7.—*Correlation coefficient between the intensity of depression at 0300 GMT and the subsequent 24-hr movement of depression*

Area*	No. of observations	Correlation coefficient from data normalized by	
		Square root transformation	Cube root transformation
Calcutta	279	0. 277‡	0. 264‡
Gopalpur	336	. 278‡	. 271‡
Allahabad	313	. 270‡	. 270‡
Nagpur	297	. 229‡	. 233‡
Delhi	98	. 116	. 173
Ahmadabad	78	. 004	. 001

*Area within 50-km radius of station
‡Significant at the 1-percent level

significant at the 5-percent level. For Nagpur and Allahabad, it is significant even at the 1-percent level. The positive value of the coefficient suggests that the higher the intensity of the depression, the greater the subsequent 24-hr rainfall, and the negative value suggests an inverse relationship. Note that west of 80°E, the values of the correlation coefficient in the left sectors are positive, and the values in the right sectors are negative. This indicates that the higher the intensity of the depression the greater the contrast between the rainfall in the right and the left sectors; conversely, the shallower the depression the smaller the rainfall contrast. Raghavan (1967) found that, during July and August, storms/depressions deprive the areas north of their track of up to 10 percent of their normal rainfall and give up to 10 percent more rainfall than normal to areas south of the track.

6. RELATION BETWEEN THE INTENSITY OF DEPRESSIONS AND SUBSEQUENT 24-HOUR MOVEMENT

Various factors operating within the atmosphere affect the motion of the monsoon depression. In an attempt to determine whether or not the intensity of the depression at 0300 GMT influences its motion during the subsequent 24-hr period, we computed the correlation coefficient between the two normalized variables (table 7).

TABLE 8.—*Some features of depression rain during July and August combined, for the period 1891–1960*

Area*	Depression days		Average rain per depression day	Standard deviation of depression rain	Contribution of depression rain to total rain for the period	Average rain per nondepression day	Efficiency of depressions as rain givers
	Number	Expressed as percentage of total period					
		(%)	(mm)	(mm)	(%)	(mm)	
Calcutta	279	6. 4	12. 4	12. 4	7. 3	10. 7	1. 16
Gopalpur	336	7. 7	9. 8	15. 7	11. 6	6. 3	1. 56
Allahabad	313	7. 2	11. 8	12. 9	8. 5	9. 8	1. 20
Nagpur	297	6. 8	24. 6	31. 1	16. 3	9. 2	2. 67
Delhi	98	2. 2	7. 8	14. 2	3. 3	5. 3	1. 47
Ahmadabad	78	1. 8	50. 8	50. 0	11. 2	7. 4	6. 86

*Area within 50-km radius of station

Except for the depressions affecting Delhi and Ahmadabad, the correlation coefficients are significant at the 1-percent level. The positive sign suggests that the higher the intensity of the depression, the greater the subsequent 24-hr motion. Although the coefficients are significant, they account for only 5–8 percent of the variance.

7. SOME FEATURES OF DEPRESSION RAIN

It is of interest to know the percentage of the total number of days that are depression days, the average rain per depression day, the variability of the depression rain, the contribution of depression rain to the total rain, and the efficiency of the depression as a rain giver in comparison to the other rain-giving factors. This climatological information has been computed for July and August during the 1891–1960 period (table 8).

East of 80°E, depression days constitute only 7 percent of the period. This value decreases to about 2 percent by longitude 75°E because many depressions weaken into Lows by the time they reach 75°E.

In the right sector, the average rainfall per depression day varies little east of 80°E, but it decreases farther west. In the left sector, average rainfall per depression day increases westward. The marked increase west of 80°E is due to the increased influx of moisture from the Arabian Sea with the strengthening of equatorial westerlies and the consequent intensification of the depression. The standard deviation of depression rain is generally of the same order as the mean.

In the right sector, depressions contribute about 7 percent of the total precipitation east of 80°E. This percentage decreases rapidly west of 80°E. In the left sector, the contribution is 12–16 percent of the total, the highest being near longitude 80°E. The contrast between the rainfall contribution by the right and the left sectors is highest along and west of 80°E.

Average rain per nondepression day varies little over the whole belt of the country from east to west. The efficiency of the depression, defined as the ratio of the average rain per depression day to the average rain per nondepression day, varies little in the right sector over different longitudes; but in the left sectors, it progressively increases from east to west, the increase being marked west of 80°E. The high efficiency of the depression as a rain giver west of 80°E illustrates the significance of depressions to the area between 18° and 25°N and west of 80°E.

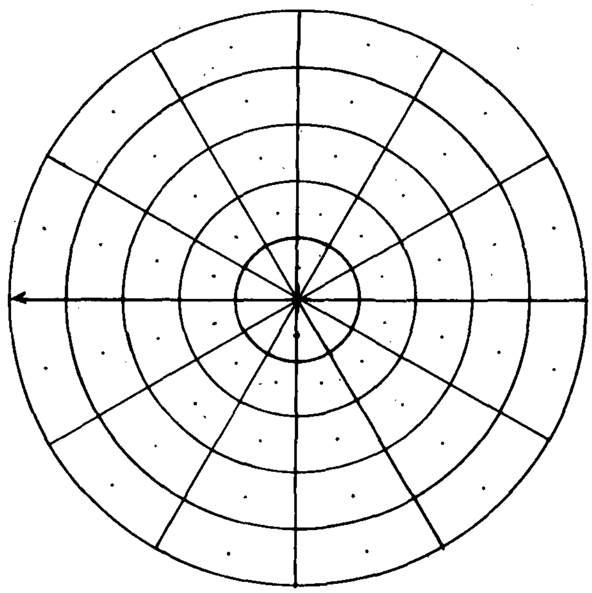

FIGURE 4.—Elements of areas (around 24-hr mean position of depression center) over which rainfall is averaged.

8. DISTRIBUTION OF RAINFALL WITHIN 500-KILOMETER RADIUS OF THE DEPRESSION CENTER ALONG THREE INDIAN LONGITUDES

Each of the semicircular right and left sectors extending 500 km from the center of the depression has been divided into 18 elements of area by circles with radii 100, 200, 300, 400, and 500 km and radial lines at angle $\theta=0$, 30°, 60°, 90°, 120° 150°, and 180° or 180°, 210°, . . ., 360°. Whenever the central station lay within any of these areas, the rainfall at and around the station was considered to have occurred at the center of the element of area. In this way, the depression rainfall at and around the six stations, Calcutta, Gopalpur, Allahabad, Nagpur, Delhi, and Ahmadabad was allocated to these elements of area. Figure 4 shows the elements of area and their centers. The center of the circle is the mean position of the depression center during the 24-hr period, 0300 GMT of one day to 0300 GMT of the next, which is the same as that for which

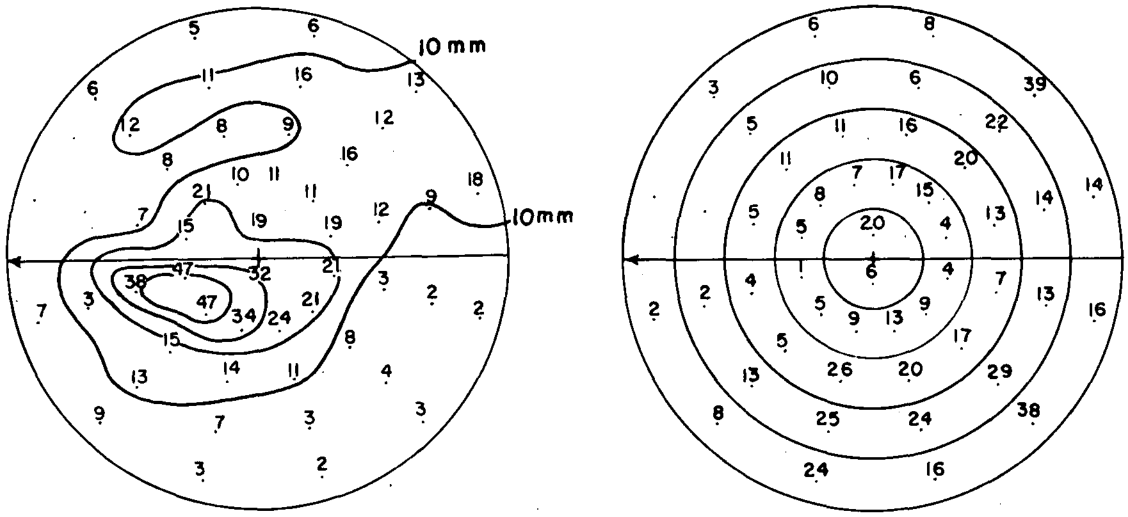

FIGURE 5.—Spatial distribution of mean 24-hr rainfall (mm) within 500 km of 24-hr mean position of depression center along longitude 87°E.

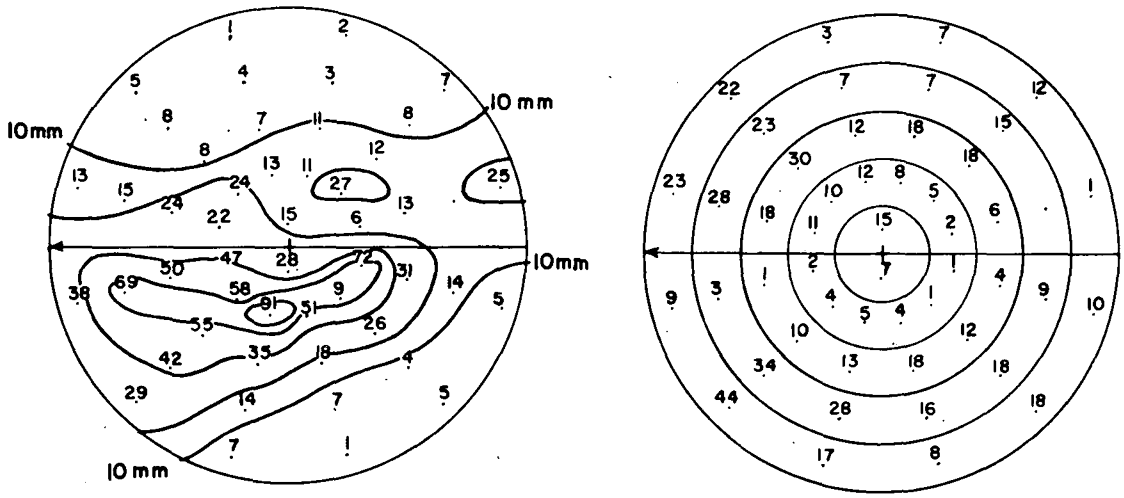

FIGURE 6.—Same as figure 5 for 80°E.

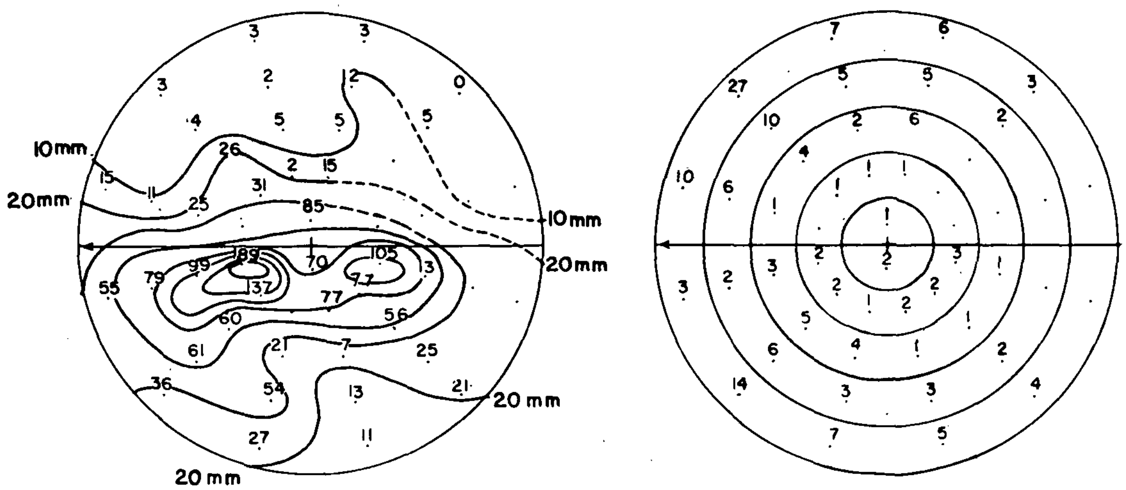

FIGURE 7.—Same as figure 5 for 75°E.

rainfall has been considered. The arrow shows the direction of motion of the depression center.

On the basis of the number of rainfall observations available for each element of area during 1891–1960, the average rainfall in millimeters was obtained for each element. Mean rainfall pictures for the right and the left sectors of the depression were obtained using the data for Calcutta and Gopalpur, respectively. Combining these two pictures, we obtained a complete picture of the mean rainfall within a 500-km radius of the depression center for the mean longitude of 87°E. Using the rainfall data for the station pairs, Allahabad-Nagpur and Delhi-Ahmadabad, we constructed pictures of mean rainfall around the depression center for the mean longitudes 80°E and 75°E in the same manner.

Figures 5, 6, and 7 illustrate the 24-hr mean rainfall around depression centers along 87°E, 80°E, and 75°E, respectively. For a few elements of area around the depression center, no rainfall observations were available for the period 1891–1960; no value is plotted near the center of these elements.

The chief features of the rainfall distribution within 500 km of the center of the Indian monsoon depression along the three longitudes may be summarized as follows: (1) The rainfall field in the right sector is relatively flat and is generally similar along the three longitudes. (2) In the left sector, maximum rainfall and the area covered by any specified isohyet increase progressively as we go westward from 87°E, with the greatest increase occurring west of 80°E. This appears to be due to the strengthening of the Arabian sea branch of the monsoon current and the consequent increase in moisture flux and the general intensification of the depressions when they move westward across 80°E. (3) Maximum rainfall is located in the left front quadrant about 150 km from the 24-hr mean center of the depression or about 300 km from the center of the depression at the beginning of the 24-hr period for which rainfall has been considered and 50–150 km from the track of the depression. (4) Heavy rainfall ($\geq$65 mm/24 hr) is found almost exclusively in the left sector, and it extends as far ahead as 500–600 km from the position of the depression center at the beginning of the 24-hr rainfall period. (5) Heavy rainfall does not appear to extend beyond 250 km from the depression track in the left sector of depression. Pisharoty and Asnani (1957) find this distance to be about 400 km.

The rainfall distribution around the depression center along the three longitudes clearly indicates that rainfall in the left sector is much higher than that in the right sector. Roy and Roy (1930) have stated that the contінous heavy rain associated with the depression is confined to the "mixed monsoon" sector in view of the active upglide surface between the "mixed" monsoon air and the "deflected" monsoon air. According to Ramanathan and Ramakrishnan (1933), heavy rain in the southwest sector is due to the ascent of old monsoon air over the fresh monsoon air, the latter air behaving as cold air relative to the former air. Sur (1933) attributed the rain over the central parts of the country, in association with the depression, to the ascent of deflected easterly winds over the fresh southwesterly maritime winds from the Arabian Sea. According to Desai (1951) and Desai and Koteswaram (1951), there is, associated with the depression, a quasi-stationary sloping partition between the relatively cold southwesterly to westerly air mass and the warm easterly air mass, and the heavy rainfall in the southwest sector is due to the ascent of the warm easterly air. Mull and

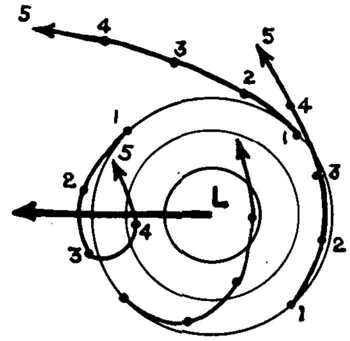

FIGURE 8.—Streamlines and air trajectories around a westward-moving depression.

Rao (1949) have suggested low-level convergence as the cause of heavy rainfall in the southwest sector.

Mulky and Banerji (1960) have shown that the circulation around the monsoon depression is asymmetric around the vertical, the axis of circulation having a pronounced tilt towards the southwest sector (i.e., the left front quadrant). During July, the representative monsoon month, the normal monsoon trough axis at sea level runs from Dacca, Bangladesh to Multan, Pakistan via Gwalior. At the 3-km level, it runs nearly along latitude 23°N. Thus, the interface between the westerlies/southwesterlies and the deflected easterlies is a southward ascending surface. The southward displacement of the trough axis with height is much larger west of longitude 80°E than east of this longitude. Even in the absence of any cyclonic system, rainfall associated with the monsoon trough is greater to the south of the trough axis at sea level than to its north due to higher convergence south of the trough axis. When there is a depression within the monsoon trough moving west-northwestward from the northern Bay of Bengal, the equatorial westerlies strengthen and convergence increases in the left sector; in addition, as a result of the motion of the depression, a further increase in the convergence in the left front quadrant occurs.

Petterssen (1956) has considered the effect of the motion of a cyclonic system on steady-state streamlines associated with a cyclonic system that moves, without alteration, in the shape of the streamline pattern. He has considered two types of cases: (1) when the velocity of air within the the cyclonic system is larger than the velocity of the cyclonic system, and (2) when the velocity of the air within the cyclonic system is smaller than that of the cyclonic system. Case (1) applies to the monsoon depression. For this case, Petterssen (1956) has given a diagram showing some typical trajectories of air parcels in the vicinity of an eastward-moving cyclonic system. His diagram adapted suitably for a westward-moving cyclonic system is given in figure 8, where thin circular lines are the streamlines, the curved lines with arrow heads show the air trajectories, and the thick straight line with arrow shows the direction of the cyclonic system. Note that the trajectories indicate higher convergence in the left front quadrant and divergence in the right rear quadrant and the adjoining right front quadrant. The highest rainfall is, therefore, found in the left front quadrant. The low rainfall in the right sector is, in general, due to divergence.

TABLE 9.—*Variation of mean depression rainfall with distance from the center of the depression*

	Left sector—Distance (km)					Right sector—Distance (km)				
	450	350	250	150	50	50	150	250	350	450
	Along longitude 87°E									
Mean rainfall (mm)	3.5	5.4	12.4	28.7	31.7	18.6	13.5	11.1	11.5	12.0
Number of observations	104	106	79	41	6	20	56	76	57	70
	Along longitude 80°E									
Mean rainfall (mm)	17.8	21.5	31.2	67.0	27.9	14.8	18.4	12.4	9.6	8.1
Number of observations	106	108	58	16	7	15	48	102	80	68
	Along longitude 75°E									
Mean rainfall (mm)	30.4	48.4	50.5	107.6	69.6	85.0	16.2	13.2	6.7	5.2
Number of observations	33	16	15	12	2	1	3	13	28	53

By averaging rainfall over semicircular strips of 100-km width, we obtained mean rainfall at different distances for the right and left secters along the three longitudes. These data are given in table 9. The variation of rainfall with distance is generally small in the right sectors, but in the left sectors it is greater. Along 87°E, rainfall is about 30 mm in the first 200 km from the center, thereafter decreasing with distance; along 80°E, it is about 70 mm between 100 and 200 km from the center, decreasing sharply for 100 km on either side, then decreasing gradually beyond 300 km; along 75°E, rainfall exceeding 100 mm occurs between 100 and 200 km from the center, decreasing sharply on both sides for 100 km from the location of maximum rainfall.

9. SUITABLE EMPIRICAL PROBABILITY MODEL FOR 24-HOUR DEPRESSION RAINFALL IN DIFFERENT QUADRANTS

Mooley and Appa Rao (1970) have shown that the gamma probability model is a good fit to pentad rainfall distribution. This would suggest that the gamma probability model may be tried for 24-hr depression rainfall. The gamma probability model was, therefore, fitted to rainfall in each of the four quadrants of the depression, and the goodness-of-fit was tested by chi-square test. In no case was the chi-square statistic significant at the 5-percent level. The fit of the gamma model to the depression rainfall in each of the four quadrants is, therefore, good. Table 10 gives the values of the chi-square statistic, degrees of freedom, and the maximum likelihood (M.L.) estimates, $\hat{b}$ and $\hat{g}$, of the scale and shape parameters, respectively, of the gamma probability model fitted to rainfall in the four quadrants of the depression. The dispersion matrix for $\hat{b}$ and $\hat{g}$ is also given in table 10.

The chief features of the table are:

1. Along 87°E: The parameter $\hat{b}$ for the left front quadrant is significantly higher than that for the left rear quadrant; the parameter $\hat{g}$ for the left front and the left rear quadrants do not appear to be significantly different from unity at the 5-percent level. The rainfall distributions in the left front and the left rear quadrants are thus not significantly different from the exponential distribution, which is a special case of the gamma distribution, or another special case of gamma distribution, the chi-square distribution with two degrees of freedom.

2. Along 80°E: The scale and the shape parameters for the left front quadrant are significantly higher than those for the left rear quadrant. The rainfall distribution in all quadrants except the left rear quadrant is not significantly different from the exponential distribution.

3. Along 75°E: Parameter $\hat{b}$ is higher for the right front quadrant than that for the right rear quadrant. The rainfall distribution in each of the quadrants is not significantly different from the exponential distribution.

The important features common to depressions along and near all the three longitudes can be summarized as follows:

1. Scale parameters in the left quadrants are significantly larger than those in the right quadrants.
2. The rainfall distribution in the left front quadrant is not significantly different from the exponential distribution.
3. In the right sectors, the change in the scale parameter with longitude is generally small; but, in the left sectors, the scale parameter increases rather markedly west of 80°E. The scale parameter of the gamma probability distribution is the ratio of the variance and the mean. Heavy to very heavy rain associated with depressions intensifying after moving west of 80°E leads to a higher value of this ratio.
4. In general, the shape parameter, $\hat{g}$, for the front quadrant is not significantly different from that for the corresponding rear quadrant.

10. PROBABILITIES OF DEPRESSION RAIN OF DIFFERENT INTENSITIES

In the preceding section, we showed that the gamma probability model gives a good fit to rainfall distribution in each of the four quadrants of a depression. In this section, probabilities of rainfall of different intensities in the four quadrants on the basis of the gamma model will be discussed.

The intensities of rainfall for which the probabilities have been computed are given in table 11. The specifications for the intensities are the same as those followed by the India Meteorological Department.

Probabilities of occurrence of rainfall of these intensities in the four quadrants of the depression along the three longitudes, 87°, 80°, and 75°E are given in table 12. Empirical probabilities of no rain are also given.

The main points of this table are:

1. In the right quadrants, probability of no rain increases westward of 87°E, but in the left quadrants, it decreases westward of 87°E.
2. In the right quadrants, the probability of heavy rain is almost zero along all the three longitudes. In the left rear quadrant, the probability of heavy rain is near zero along 87°E.
3. The probability of heavy rain in the left front quadrant increases westward of 87°E.
4. The probability of heavy or very heavy rain in the left quadrants is much higher along longitude 75°E than along 80°E.

The information given in table 12 can be used by a forecaster at any of the six stations, Calcutta, Allahabad, Delhi, Gopalpur, Nagpur, and Ahmadabad. Using the current and past charts, he must estimate the 24-hr mean location of the center of the depression and determine the quadrant of the depression in which his station is expected to lie. Thereafter, he can use table 12 as an aid

TABLE 10.—*Chi-square test for the null hypothesis that 24-hr rainfall in different quadrants of a monsoon depression is gamma distributed and parameters of the fitted gamma distribution (start of the distribution is at zero)*

Area*	Number of observations	Quadrant	X^2_0	d.f.	Scale parameter $\hat{b}$ (mm)	Shape parameter $\hat{g}$	Dispersion Matrix: Var $(\hat{b})$ / Cov $(\hat{b},\hat{g})$	Cov $(\hat{b},\hat{g})$ / Var $(\hat{g})$
Calcutta	81	1	8.268	6	7.88	1.472	1.8	−0.24
							−0.24	0.044
	198	2	15.205	9	8.82	1.465	0.93	−0.11
							−0.11	0.018
Gopalpur	105	3	2.915	6	17.13	1.017	7.1	−0.26
							−0.26	0.015
	209	4	4.581	5	11.62	0.881	2.5	−0.11
							−0.11	0.008
Allahabad	206	1	10.500	9	12.44	1.123	2.0	−0.12
							−0.12	0.011
	107	2	5.031	6	9.03	1.265	2.1	−0.20
							−0.20	0.027
Nagpur	171	3	8.299	9	35.87	0.973	20.5	−0.33
							−0.33	0.009
	126	4	10.357	6	21.89	0.687	12.4	−0.19
							−0.19	0.006
Delhi	75	1	2.381	4	14.73	0.895	11.9	−0.42
							−0.42	0.025
	23	2	1.842	2	7.90	1.138	10.3	−0.95
							−0.95	0.137
Ahmadabad	52	3	7.501	4	46.78	1.192	102.5	−1.71
							−1.71	0.044
	26	4	4.939	2	47.87	0.895	241.7	−2.60
							−2.60	0.049

*Area within 50-km radius of station

for forecasting, 24-hr in advance, the probability of rainfall of any particular intensity at his station.

11. CONCLUSIONS

On the basis of the study of depressions during July and August for the period 1891–1960 and the associated rainfall, the following conclusions can be drawn:

1. The 24-hr motion of the monsoon depression is gamma distributed.
2. Along and west of 80°E, the higher the intensity of the depression, the greater the contrast in rainfall in the right and the left sectors.
3. Depression days constitute about 7 percent of the period east of 80°E, decreasing westward to about 2 percent at 75°E.
4. In the left sector, the mean rainfall per depression day increases westward, the increase being greatest west of 80°E. The standard deviation of the depression rain is of the same order as the mean.
5. In the right sector, rainfall contribution by the depressions is about 7 percent of the total rainfall east of 80°E, decreasing westward rapidly; in the left sector, the contribution is 12–16 percent with the highest near longitude 80°E.
6. In the right sector, the efficiency of the depression as a rain giver varies little with longitude; in the left sector, it progressively increases from east to west, the increase being greatest west of 80°E.
7. In the right sectors, the rainfall field is flat; in the left sector, the maximum rainfall increases westward from 87°E, with the greatest increase west of 80°E.
8. Maximum rainfall is located in the left front quadrant about 150 km from the 24-hr mean center of the depression, or 300 km from the center of the depression at the beginning of the 24-hr period for which rainfall is considered, and 50–150 km from the track of the depression.

TABLE 11.—*Specifications of rainfall intensities*

Rainfall intensity	Specification (24-hr rainfall) (R) (mm)
Light	$R \leq 7.5$
Moderate	$7.6 \leq R \leq 34.9$
Rather Heavy	$35.0 \leq R \leq 64.9$
Heavy	$65.0 \leq R \leq 84.9$
Very Heavy	$85.0 \leq R$

TABLE 12.—*Probabilities of 24-hr rainfall of different intensities in the quadrants of monsoon depression along three Indian longitudes*

Quadrant	Probability of: No rain	Light rain	Moderate rain	Rather heavy rain	Heavy rain	Very heavy rain
			Longitude 87°E			
1	0.00	0.42	0.55	0.03	0.00	0.00*
2	.01	.37	.58	.04	.00	.00
3	.17	.29	.43	.09	.02	.00
4	.31	.37	.29	.03	.00	.00
			Longitude 80°E			
1	.09	.06	.48	.07	.00	.00
2	.12	.39	.46	.03	.00	.00
3	.06	.19	.41	.20	.06	.08
4	.11	.41	.38	.08	.01	.01
			Longitude 75°E			
1	.36	.29	.30	.05	.00	.00
2	.35	.36	.28	.01	.00	.00
3	.00	.10	.34	.24	.10	.22
4	.04	.18	.37	.20	.08	.13

* Very low probabilities are denoted by 0.00.

9. In the left sector, heavy rainfall extends 500 to 600 km ahead of the depression center at the beginning of the 24-hr period and about 250 km from the depression track.

10. The gamma probability model is a good fit to rainfall in each of the four quadrants of monsoon depression along longitudes 87°, 80°, and 75°E. Rainfall distribution in the left front quadrant along each of the longitudes is not significantly different from the exponential distribution, which is a special case of the gamma distribution. The scale parameters of the gamma distribution in the left quadrants are significantly higher than those in the right quadrants along each of the three longitudes. In the right sectors, the change of the scale parameter with longitude is generally small; in the left sector, the scale parameter increases markedly west of 80°E.

11. The probability of heavy and very heavy rain in the left front quadrant increases appreciably westward.

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